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Influences of Bladders and Phase Change Materials in Anti-G Suit on Pilots' Thermal Responses

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Abstract

A heat and humidity transfer model for the pilot wearing bladder anti-G garment system is developed. In the model, an 85-node human thermoregulatory model is developed for predicting pilots' thermal stresses and the coupled heat and humidity transfer equations including latent heat sorption/release of the Phase Change Materials (PCM) are utilized for the garment. Meanwhile, the garment inner boundary conditions are treated by considering the bladder effects. Also, the model is validated by comparing the simulation with experimental results. After the validation, water vapour concentration and temperature at different parts of garment and evaporation heat loss, dry heat loss and skin temperature at different parts of body are predicted and compared to study the influences of bladder. Otherwise sweat rate, sweat accumulation, mean skin temperature and comprehensive index of thermal stress under garments with different volumetric fractions of PCM are also predicted and compared to study the influences of PCM. The conclusion shows that bladders will produce more heat stress on wearers and PCM can improve the thermal performance of the bladder anti-G garment.

Keywords: Bladder anti-G Garment; PCM; Human Thermoregulatory Model; Thermal Stress

1 Introduction

To protect the fighter pilots from injurious G-load resulting from fighter high acceleration, bladder anti-G garments are designed specially. The bladders are impermeable, they will be flatted and will compress skin surface to protect pilots from blacking-out during periods of high acceleration. Because of impermeable bladders and high thermal resistance, anti-G garments always produce heat stress on wearers even in a moderate environment. The heat stress will reduce pilots' work efficiency and decrease their endurance to the high G-load. To mitigate pilot heat stress in various environments, research on thermal performance of anti-G garment is essential to provide critical information for improving the garment design. In the past years, many models for the general

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clothing or the clothed human body have been developed. For human body, Gagge [1] developed a 2-node model and divided human body into two layers, core and skin which have the same temperature in each layer. Gagge's model is simple and useful in homogeneous conditions, but it cannot describe human body accurately in a complex and polytropic environment. Therefore, Jones [2] divided the layer of skin into multiple nodes based on a two-node model. Alireza and Mehdi [3] presented a simplified three-node model, in which the passive system of the human body is considered as core, bare skin, and clothed skin compartments, and the relative energy balance equation is used to determine the human thermoregulatory parameters. Stolwijk [4] developed a 25-node model including 6 segments and each segment were divided into core, muscle, fat and skin layers. Stolwijk's model is mostly complete and can simulate sweating and shivering accurately except for considering sweat accumulation on skin. Wafaa and Nesreen [5] improved an arterio-venous anastomoses model of the digits to accurately predict skin blood flow rate in the hands and fingers, and the local and overall human thermal responses in transient environments. For anti-G garments, Qiu Yifen [6] developed a thermal performance analysis model of bladder anti-G garments based on thermal and moisture resistance model of the garment and human bioheat transfer equations. However, the thermal resistance and moisture resistance are measured under steady-state conditions, which cannot fully describe the real heat transfer process within the anti-G garments. To consider the coupled heat and humidity transfer processes in the anti-G garment, the fiber hygroscopicity must be taken account. Li and his collaborators [7-11] developed a series of the garment models, in which the water vapor diffusion, moisture absorption/desorption by the fibers, liquid water penetration due to capillary pressure, evaporation/condensation, phase change heat generation, radiation and pressure gradient have been taken into the model gradually. Some models have been used to simulate thermal responses of clothed human body model [12]. However, the above mentioned are only for general garments. To overcome the disadvantage of the thermal and moisture resistance model for garment and discuss the improvement of thermal performance method for the bladder anti-G garment, this paper combines the coupled heat and humidity transfer model for garment and an improved human thermoregulatory model to study the thermal performance of bladder anti-G garment. Influences of bladders and phase change materials in anti-G suit on pilots' thermal responses are analyzed using this model respectively.

2 Mathematical Models

The mathematical models include human thermoregulatory model, clothing heat and humidity transfer model and boundary conditions.

2.1 85-node Human Thermoregulatory Model and Index of Heat Stress

To consider the bladder effect on the human body temperature, the 25-node Stolwijk's model [4] and 61-node model of Salloum and Ghaddar [13] are improved in this paper. Fig. 1 (a) shows the controlled system of human body. The whole human body is divided into 21 segments, and the abdomen, front of left thigh, front of right thigh, front of left lower leg and front of right lower leg, which are near the bladders, are separated from the trunk, legs in Stolwijik's model so that influences of bladders on pilots' thermal responses can be researched more accurately. Also, each segment is subdivided into 4 layers: core, muscle, fat, and skin, as shown in Fig. 1 (b). Similar